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Preliminary Experiment on the Negative Magneto-Resistance Effect in a Weakly Ionized Discharge Plasma

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Abstract : Compared with the interest in the magneto-resistance effect in solid conductors, the effect in a gas plasma has hardly been addressed.

In this work, a theoretical result that a magneto-resistance in an infinite plasma decreases is examined experimentally in an actual discharge plasma. Furthermore, a modified expression for the ambipolar diffusion coefficient in the case where electrons are scattered by heavy neutral atoms is presented.

KEY WORDS : Glow discharge, Transverse magnetic field, Negative resistance.

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* Visiting Research Associate (April 1999∼March 2001)

1. Introduction

When a Hall current in an infinite plasma is inhibited due to some physical condition, a Hall electric field is generated in the opposite direction to the Hall current. This Hall electric field increases the original discharge current by about 10 percent (M. Nagata : J. Plasma Phys. 44 (1990) 47). In an actual discharge tube, electron density is not uniform, and therefore the theory in the infinite plasma must be modified by taking the mechanism of the ambipolar diffusion into consideration. The purpose of this work is to examine the magnetic field-dependence of a discharge current in an actual discharge tube, from both theoretical and experimental points of view.

Let us consider a plasma having a rectangular cross section rather than a cylindrical one, since the former is easier to handle theoretically.

Then we set an x-y-z coordinate system with the origin 0 located at the center of the cross section, as shown in Fig.1. A discharge current flows in the direction of −z axis. A magnetic flux density $\vec{B}$ is applied in the direction of +y axis. An electric field $\vec{E}$ in a plasma is assumed to be small in magnitude. Let us consider the case where $\vec{E}$ has x and z components. We deal with the y component of $\vec{E}$ as zero, since it does not interact with $\vec{B}$. The drift velocity of electrons is derived in section 2, and then in section 3, a modified ambipolar diffusion coefficient is given. In section 4, an electron density distribution under the Hall effect and an ambipolar diffusion mechanism is calculated. In section 5, we examine what effect $\vec{B}$ has on the discharge current in the −z

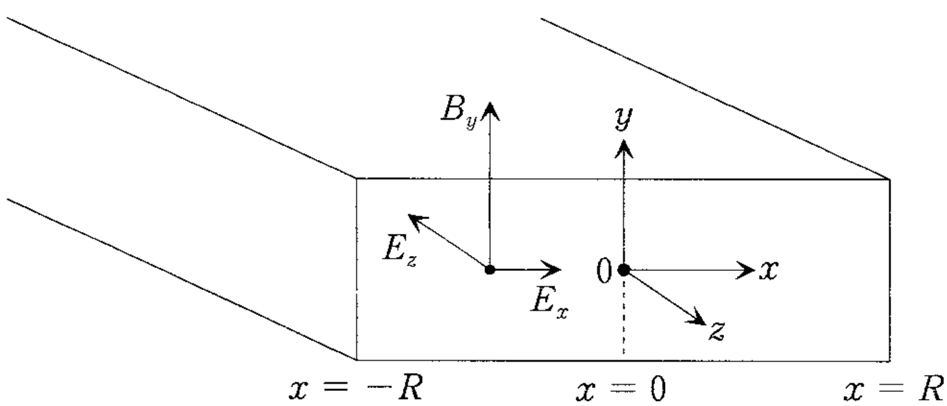

Fig.1 The coordinate system and the force fields.

direction. With respect to collisions, only the collisions between electrons and neutral atoms are considered. Neutral atoms are regarded as heavy rigid spheres. Finally in section 6, the result of a simple preliminary experiment is reported.

2. A drift velocity

The electric field $\vec{E}$ and the magnetic field $\vec{B}$ are set as

$$\left.\begin{aligned} \vec{E} &= \hat{x}E_x - \hat{z}E_z \\ \vec{B} &= \hat{y}B_y \end{aligned}\right\} \tag{1}$$

It should be noted that E_x is a function of x. An equation for the drift velocity (denoted by $\vec{u}(=\hat{x}u_x+\hat{z}u_z)$) in a steady state $(d\vec{u}/dt=0)$ is given by

$$0 = -n_e q\left[\hat{x}E_x+\hat{z}(-E_z)\right] - n_e q\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ u_x & 0 & u_z \\ 0 & B_y & 0 \end{vmatrix}$$

$$-n_e \nu m_e(\hat{x}u_x+\hat{z}u_z)$$

$$-n_e\beta_1\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ -qE_x & 0 & qE_z \\ 0 & 1 & 0 \end{vmatrix} + n_e\beta_2\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 0 & 1 & 0 \\ -qE_z & 0 & -qE_x \end{vmatrix} \tag{2}$$

(from $(37)_{c\to\infty}$ of ref. (Nagata, M. : J. Plasma Phys. 44(1990) 47), where c is the light speed)

where n_e is a local average electron density which is a function of x, $-q$ the electron charge, m_e the rest mass of an electron, $\nu(\equiv\tau^{-1})$ the mean collision frequency of electrons in the electron-neutral collisions (Electron temperature is assumed to be uniform in a discharge tube),

$$\beta_1 = \frac{-\frac{1}{3}\omega_c\tau}{1+\omega_c^2\tau^2} \qquad \left(\text{where } \omega_c = \frac{q|\vec{B}|}{m_e}\right),$$

and

$$\beta_2 = \frac{\frac{1}{3}}{1+\omega_c^2\tau^2}.$$

The solution of (2) is

$$u_x = \frac{\frac{-q}{m_e\nu}(1-\beta_2-\beta_1\omega_c\tau)}{1+\omega_c^2\tau^2}E_x + \frac{\frac{q}{m_e\nu}(\omega_c\tau+\beta_1-\beta_2\omega_c\tau)}{1+\omega_c^2\tau^2}E_z$$

$$\equiv -\mu_{e1}E_x+\mu_{e2}E_z \tag{3}$$

$$u_z = \mu_{e2}E_x+\mu_{e1}E_z \tag{4}$$

3. A modified ambipolar diffusion coefficient

Let us consider the case where an ion charge is $+q$. If diffusion currents are taken into account, an electron current density i_{ex} and an ion current density i_{ex} in the x direction are written as

$$i_{ex} = n_eq\mu_{e1}E_x - n_eq\mu_{e2}E_z + qD_e\frac{dn_e}{dx} \tag{5}$$

$$i_{ix} = n_iq\mu_{i0}E_x - qD_{i0}\frac{dn_{i0}}{dx} \tag{6}$$

where, μ_{i0}, n_i and D_{i0} are the ion mobility, the local average ion density and the ion diffusion coefficient, respectively, in the case where $B_y = 0$.

Since this work deals with such a weak magnetic field as $0 \leqq \omega_c \tau < 1$, the effects of the magnetic field on the ion mobility and the ion diffusion coefficient are neglected. From the following conditions :

$$\left.\begin{aligned} n_e &= n_i \equiv n_0 \\ i_{ex} + i_{ix} &= 0 \end{aligned}\right\}, \tag{7}$$

one obtains

$$n_0 q(\mu_{e1} + \mu_{i0}) E_x + q(D_e - D_{i0}) \frac{dn_0}{dx} - n_0 q \mu_{e2} E_z = 0 \tag{8}$$

and from (8)

$$E_x = \frac{\mu_{e2}}{\mu_{e1} + \mu_{i0}} E_z - \frac{D_e - D_{i0}}{\mu_{e1} + \mu_{i0}} \frac{dn_0}{dx} \frac{1}{n_0} \tag{9}$$

Substituting (9) into (5) gives

$$i_{ex} = q\left[\frac{D_{i0}\mu_{e1} + D_e \mu_{i0}}{\mu_{e1} + \mu_{i0}}\right] \frac{dn_0}{dx} - n_0 q \frac{\mu_{e2}\mu_{i0}}{\mu_{e1}} E_z \tag{10}$$

From (10), a modified ambipolar diffusion coefficient D_{ambi} is obtained as

$$\begin{aligned} D_{ambi} &= \frac{D_{i0}\mu_{e1} + D_e \mu_{i0}}{\mu_{e1} + \mu_{i0}} \simeq D_{i0} + \frac{\mu_{i0}}{\mu_{e1}} D_e \\ &\simeq \frac{\mu_{i0}}{\mu_{e1}} D_e = \frac{1}{1 - \beta_2 - \beta_1 \omega_c \tau} \left(\frac{\mu_{i0} D_{e0}}{\mu_{e0}}\right) \end{aligned} \tag{11}$$

Here, the following quantity and relationships have been employed :

$$\left.\begin{aligned} &\mu_{e0} = \frac{q}{m_e \nu} \qquad D_e = \frac{D_{e0}}{1 + \omega_c^2 \tau^2} \\ &\frac{D_{e0}}{\mu_{e0}} \simeq \frac{k_B T_e}{q} \gg \frac{D_{i0}}{\mu_{i0}} \simeq \frac{k_B T_i}{q} \end{aligned}\right\}, \tag{12}$$

where, k_B is the Boltzmann constant, T_e electron temperature and T_i ion temperature. It is noted that the ion cyclotron frequency has been treated as zero in (11). D_{ambi} changes from $(3/2)(\mu_{i0}D_{e0}/\mu_{e0})$ to $(3/4)(\mu_{i0}D_{e0}/\mu_{e0})$ as $\omega_c\tau$ increases. The quantity $\mu_{i0}D_{e0}/\mu_{e0}$ is the approximate expression for the classical ambipolar diffusion coefficient.

4. An electron density distribution

In order to derive an electron density distribution $n(x)$ in the x direction, let us consider the increment, $d[n(x)(1\times dx)]/dt$, per unit time of the number of electrons in the small volume shadowed by oblique lines in Fig.2. Since the increment is zero in steady state, one has

$$\begin{aligned}\frac{d[n(x)dx]}{dt} &= \left(-D_{ambi}\frac{dn(x)}{dx}+\frac{\mu_{e2}\mu_{i0}E_z}{\mu_{e1}}n(x)\right)\\ &-\left(-D_{ambi}\frac{dn(x+dx)}{dx}+\frac{\mu_{e2}\mu_{i0}E_z}{\mu_{e1}}n(x+dx)\right)\\ &+n(x)\ \nu_{net}\ dx=0\end{aligned} \tag{13}$$

where ν_{net} = (a mean ionization frequency)
− (a mean recombination frequency).

From (13), the following differential equation is obtained :

$$\frac{d^2n(x)}{dx^2}-\left(\frac{\mu_{e2}\mu_{i0}E_z}{\mu_{e1}D_{ambi}}\right)\frac{dn(x)}{dx}+\frac{\nu_{net}}{D_{ambi}}n(x)=0 \tag{14}$$

A solution satisfying $n(x)=0$ at the tube wall is given by

$$\begin{aligned}n(x) &= e^{\alpha' x}(A_0\cos\gamma' x+B_0\sin\gamma' x)\\ &\equiv n_m e^{\alpha' x}\cos[\gamma'(x-\Delta x)]\end{aligned} \tag{15}$$

where, A_0 and B_0 are arbitrary constants,

$$\alpha' = \frac{1}{2}\frac{\mu_{e2}}{\mu_{e1}}\frac{\mu_{i0}E_z}{D_{ambi}},$$

$$\beta' = \left(\frac{\nu_{net}}{D_{ambi}}\right)^{1/2},$$

$$\gamma' = (\beta'^2 - \alpha'^2)^{1/2}$$

$n_m = n^{(0)} + \Delta n$ (where, $n^{(0)}$ is the maximum value of $n(x)$ at $B_y = 0$)

Based on (15), the form of $n(x)$ is supposed to be such as shown in Fig.3.

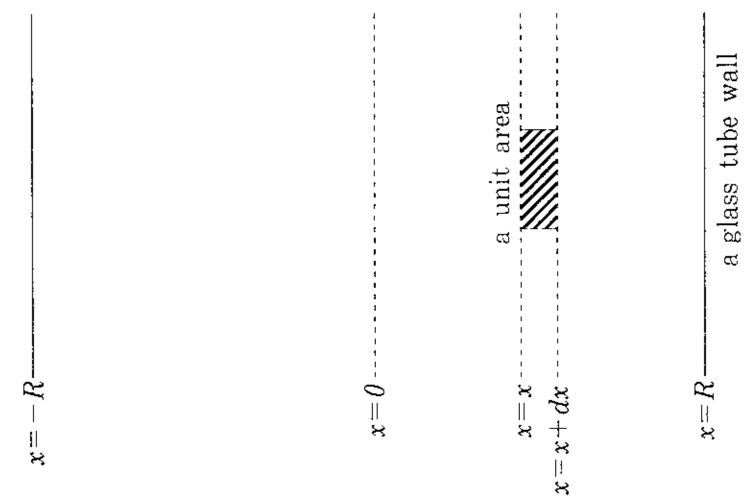

Fig.2 A diagram to derive an equation for an electron density distribution in the x direction.

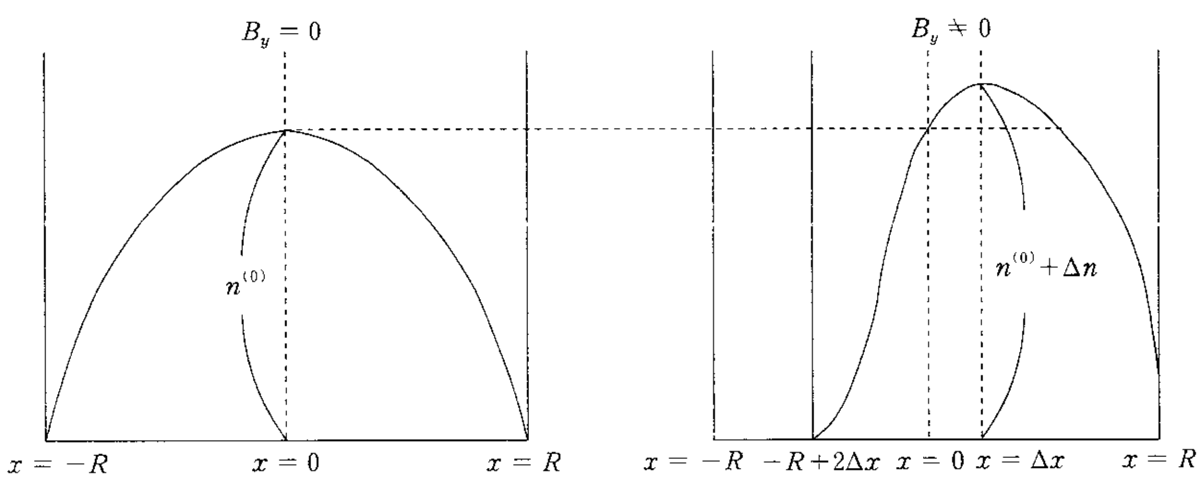

Fig.3 The presumption of variation of the electron density distribution by virtue of the magnetic field B_y.

5. A discharge current I_z in the z direction

(A) $B_y = 0$

$$
\begin{aligned}
I_{z(B_y=0)} &\equiv I_0 \\
&= K\int_{-R}^{R} n^{(0)} \cos\beta_0' x \times (-q) \times \mu_{e1(B_y=0)} E_z\, dx \\
&= K n^{(0)} (-q) \frac{2}{3} \mu_{e0} \frac{2}{\beta_0'} E_z
\end{aligned}
\qquad (16)
$$

where, $\beta_0' = \beta'_{(B_y=0)} = (\nu_{net} / D_{ambi(B_y=0)})^{1/2}$, and K is a quantity resulting from the integration with respect to y.

(B) $B_y \neq 0$

$$
I_z = K\int_{-R+2\Delta x}^{R} n_m e^{\alpha' x} \cos[\gamma'(x-\Delta x)] \times (-q)(\mu_{e1} E_z + \mu_{e2} E_x)\, dx \qquad (17)
$$

From (9) and (15), one has

$$
\begin{aligned}
E_x &\simeq \frac{\mu_{e2}}{\mu_{e1}} E_z - \frac{D_e}{\mu_{e1}} \frac{1}{n(x)} \frac{dn(x)}{dx} \\
&= \frac{\mu_{e2}}{\mu_{e1}} E_z - \frac{D_e}{\mu_{e1}} \alpha' + \frac{D_e \gamma'}{\mu_{e1}} \tan[\gamma'(x-\Delta x)]
\end{aligned}
\qquad (18)
$$

where the second term is, from (11),

$$
-\frac{D_e}{\mu_{e1}} \alpha' \simeq -\frac{\mu_{e2}}{2\mu_{e1}} E_z \qquad (19)
$$

Substituting (19) into (18) and then substituting the resultant E_x into (17), one has

$$I_z = Kn_m(-q)\,\mu_{e1}E_z \frac{\gamma'}{\alpha'^2+\gamma'^2}\,(e^{\alpha' R}+e^{-\alpha' R-2\alpha'\Delta x})$$

$$+Kn_m(-q)\mu_{e2}\left\{\frac{\mu_{e2}}{2\mu_{e1}}E_z\frac{\gamma'}{\alpha'^2+\gamma'^2}\,(e^{\alpha' R}+e^{-\alpha' R-2\alpha'\Delta x}) + \frac{D_e\gamma'}{\mu_{e1}}\frac{\alpha'}{\alpha'^2+\gamma'^2}\,(e^{\alpha' R}+e^{-\alpha' R+2\alpha'\Delta x})\right\} \tag{19}$$

Using $\alpha'^2+\gamma'^2=\beta'^2$, (19) is simplified into

$$I_z = K_z\left(\mu_{e1}E_z+\frac{\mu_{e2}^2}{\mu_{e1}}E_z\right) \tag{20}$$

where

$$K_z = K(n^{(0)}+\Delta n)(-q)\frac{\gamma'}{\beta'^2}\,(e^{\alpha' R}+e^{-\alpha' R-2\alpha'\Delta x}). \tag{21}$$

The quantity I_z reduces to I_o given in (16) at the limit $B_y \to 0$. As B_y increases to a very strong level, $\gamma'(=(\beta'^2-\alpha'^2))$ tends to zero and then the discharge approaches a vanishing state.

6. An experiment

The purpose of the experiment in this work is to examine the variation of (20) by the magnetic field B_y. If the coefficient K_z in (20) changes little by application of B_y, I_z of (20) shows variation in the same manner as derived in the case of an infinite plasma (M. Nagata : J. Plasma Phys. 44 (1990) 47, σ'_{mag} in figure 1). In this work, we report a preliminary experiment using only a piece of sealed Neon discharge tube at 5 [Torr]. A cylindrical tube has been adopted rather than a rectangular tube, since the former is stronger than the latter against atmospheric pressure. The magnetic field has been generated by flowing a current in a coil wound around an iron core. An output is 25 [Gauss] per 0.1 [A]. A constant voltage supply has been connected between the anode and the cathode. Both of the anode and the cathode are made of Aluminum.

The configuration of the discharge tube and the magnet is shown in Fig.4.

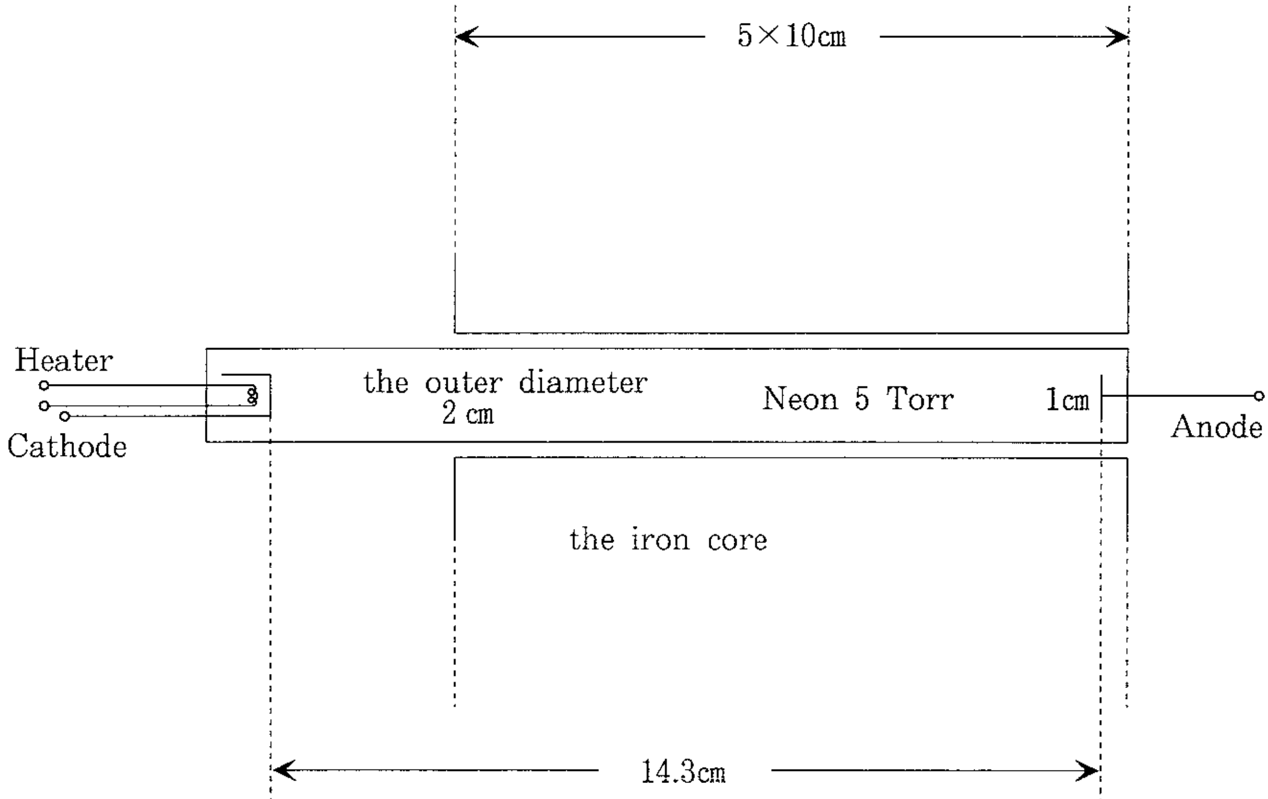

Fig.4. The discharge tube and the magnet

The basic physical quantities of a discharge plasma in this experiment are as follows, under the condition of (Neon gas pressure P =5 Torr, Neon gas temperature T_{Ne} =300K, B_y =100 Gauss) :

* In a normal glow discharge, a mean thermal velocity $\bar{v}$ is supposed to be

$$\bar{v} = 10^6 \ m/\sec$$

* The collision cross section σ_{Ne-e} is

$$\sigma_{Ne-e} = 2.54\times10^{-20}\ m^2 \quad at \quad \bar{v} = 10^6 \ m/\sec$$

* The Neon atom density n_{Ne} is

$$n_{Ne} = \frac{P}{k_B T_{Ne}} = \frac{\frac{5\times10^5}{760}}{1.38\times10^{-23}\times300} = 1.6\times10^{23} m^{-3}$$

* The mean free path λ of electrons is

$$\lambda = \frac{1}{n_{Ne}\sigma_{Ne-e}} = 0.24 \ mm$$

* The mean collision time τ of electrons is

$$\tau = \frac{\lambda}{\bar{v}} = 2.4 \times 10^{-10} \quad \sec$$

* The cyclotron angular frequency ω_c of an electron with $\bar{v} = 10^6 \ m/\sec$ is

$$\omega_c \tau = \frac{qB_y}{m_e}\tau = \frac{1.6\times10^{-19}\times100\times10^{-4}}{9.1\times10^{-31}}\times2.4\times10^{-10} = 0.44.$$

For a small magnetic field, the two factors in K_z given in (21) beomes approximately

$$\frac{\gamma'}{\beta'^2} \simeq \frac{1}{\beta'} = \frac{1}{\beta'_0}\left(\frac{2}{3}\,\frac{1}{1-\beta_2-\beta_1\omega_c\tau}\right)^{1/2} \tag{21}$$

$$e^{\alpha' R} + e^{-\alpha' R \mp 2\alpha'\Delta x} \simeq 2 + \alpha'^2 R^2 \tag{22}$$

Equation (21) is a slowly decreasing function, while (22) is a slowly increasing function. Accordingly, if the variations of (21) and (22) balance each other, the discharge current is to show a negative resistance (the increase of the discharge current for the increase of the magnetic field).

Now, an experimental result which shows the basic characteristics with respect to the variation of the total discharge current for the magnetic field is shown in Fig.5. However, we came across two following obstructions which throw doubt on the confidence of this experimental result :

(i) The magnitude of the discharge current varied ceaselessly at random within ± 5 percent.

(ii) The emitting light color changed from red to white-pink color after about a one hour experiment.

Though we met with such obstructions, we could confirm that, in the beginning stage of the magnetic field, the phenomenon in which the discharge current slightly increases certainly exists.

We are planning to make a more detailed experiment.

The author expresses sincere thanks to Professor M. Sato for his precious advices and kind instruction. Also the author is grateful to Professor T. Watari, Professor S. Sudo and Professor K. Yamazaki for precious discussions about our experimental study.

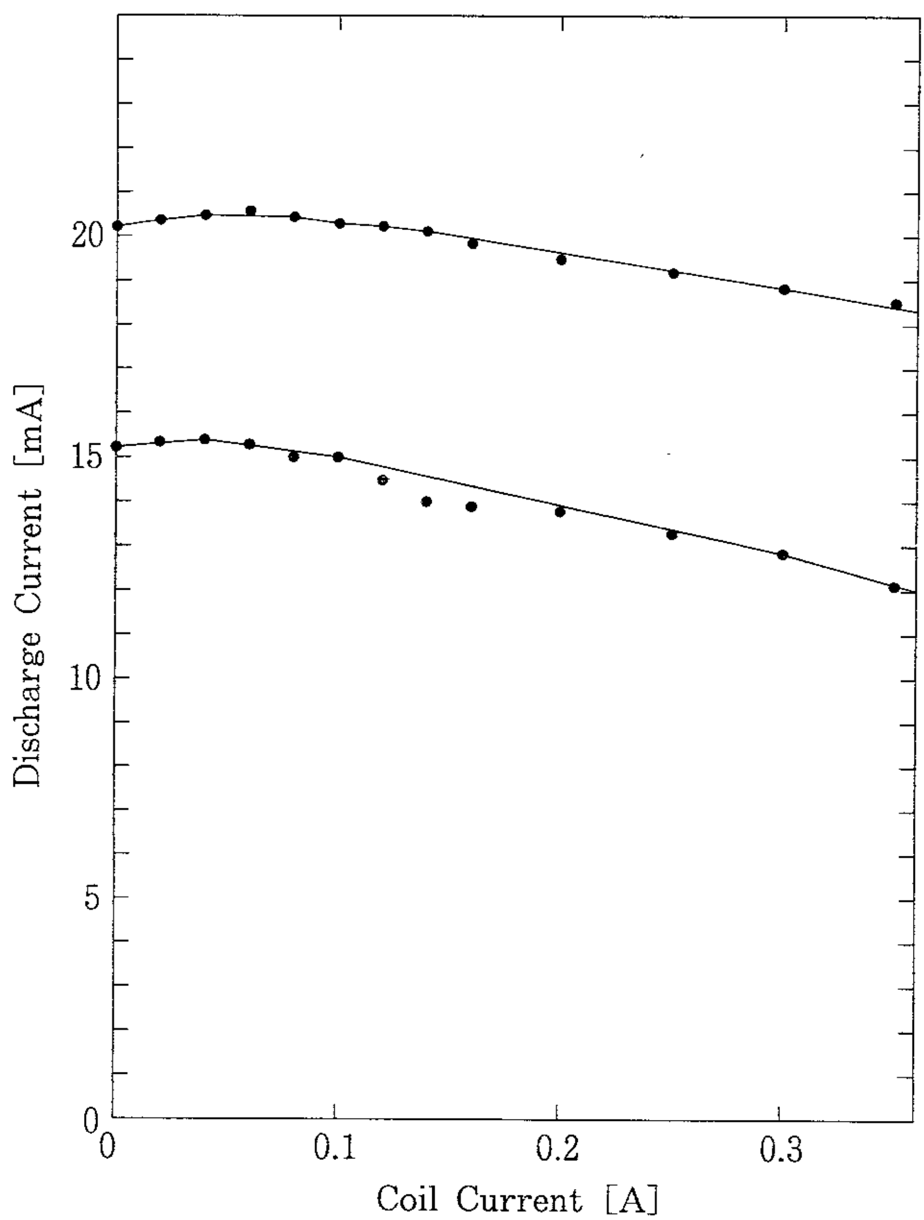

Fig.5 The discharge current characteristics for the magnetic field (250 Gauss／Ampere).

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